Automatic Tap Voltage Regulator Connected in Closed Delta

Carvalho, M.R.
Research and Development Dept.
Daimon Engenharia e Sistemas
São Paulo - SP - BR
marcus@daimon.com.br

Enomoto, B.Y.
Research and Development Dept.
Daimon Engenharia e Sistemas
São Paulo - SP - BR
bruno.enomoto@daimon.com.br

Nanni, M.
Research and Development Dept.
Daimon Engenharia e Sistemas
São Paulo - SP - BR
nanni@daimon.com.br

Oliveira, C.C.B.
Research and Development Dept.
Daimon Engenharia e Sistemas
São Paulo - SP - BR
barioni@daimon.com.br

***Abstract*—In this paper, a three-phase power flow for electrical distribution systems considering load change conditions and an automatic tap voltage regulator connected in closed-delta. An automatic Voltage Regulator is an equipment that maintains the voltage level regardless the load variations, under certain limits. The methodology was tested on the IEEE34 bus distribution system.**

***Keywords*- Distribution System, Voltage Control, Power system dynamic stability**

I. INTRODUCTION

Every customer on a distribution feeder must be supplied with a voltage that is within ANEEL standards [1]. ANEEL (Brazilian Electricity Regulatory Agency) is a regulatory agency, in charge of regulation and supervision of the production, transmission and marketing of electric energy in accordance with the Policies and Guidelines of the Brazilian Federal Government. Every customer's voltage will vary as the load on the feeder varies. In order to satisfy the ANEEL standards, the electrical utility must have ways to regulate the feeder voltage. The two most common methods are the application of switched shunt capacitors and step voltage regulators. The step voltage regulators may be located in the distribution substation or downstream from the substation. The distribution engineer must have a way to analyze the feeder voltages in the present and in the future. This is typically done with the application of a power flow program such as Daimon's InterPlan™ [2]. The power flow program must be capable of modeling both the shunt capacitors and the Step Voltage Regulators (SVR). The modeling of shunt capacitors will not be discussed in this paper.

The modeling of SVR can be complex, in particular, the critical is to model the compensator circuit since it is the control which determines when a tap change is necessary. The compensator model will include the voltage level, the bandwidth and the R and X settings. This paper will discuss the modeling of the SVR and then its application in controlling the feeder voltage.

Among several aspects that are regulated and supervised by ANEEL like voltage level in Power Distribution System (PDS). This item is regulated by ANEEL resolution 505 of November 2001, which "provides updated and consolidated the provisions on compliance levels of voltage of electrical power in steady state conditions". Inadequate voltage level can cause several problems to the customers. Overvoltage and undervoltage prolonged cause incorrect equipment operation, as speed changes of electrical machines and brightness changes of a lamp. Undervoltage can cause overheat on induction engines (SHORT, 2004).

This paper presents a three-phase power flow for PDS considering the presence of SVR. A SVR is a device that keeps a predetermined voltage in a distribution line in despite of the load variations within its rated power. It consists of an autotransformer able to increase or reduce its output voltage through an automatic tap changing. The command of the commutation mechanism can be done automatically or by manual operation. The SVR is equipped with controls and accessories to make it possible to adjust the tap level automatically under load conditions. As these accessories are sensitive to voltage variations, it keeps the output voltage within a determined range. The most common device is a mono-phase regulator that can be used in mono-phase systems or in three-phase PDS, with three mono-phase regulators connected in Wye-grounded or closed delta conforming the three-phase regulator bank. Alternatively, two regulators can be connected in open delta, in such a case, only two of the three voltages are controlled.

The paper presents a methodology for automatic calculation for the tap level in SVR in closed delta, which main objective

Daimon Engenharia e Sistemas

is to keep the voltage levels within limits established in the ANEEL resolution 505, improving the quality of energy dispatched to costumers and reducing costs to the electrical utilities.

Non linear conditions for the PDS will be considered, as well as asymmetric mutual coupling between the phases through the running of a three-phase power flow process.

A SVR is able to control the voltage bus where it is located, or to control the voltage of a distant bus. There are many power flow algorithms that can be used to obtain the steady state voltage conditions of an electrical system. In this paper the three-phase backward/forward sweep algorithm presented in [3] was implemented. This algorithm is commonly applied on radial distribution systems, and is widely used by researchers and electrical utilities.

To test the efficiency of the proposed methodology, the IEEE 34 node distribution test system is used. This system has two voltage regulators.

II. METHODOLOGY

A. *Mathematical Model of Voltage Regulators*

Step Voltage Regulators (SVR) are autotransformers with automatic tap level adjustment under load. Usually, the SVRs operate in steps in the range of -10% and +10% of gain, divided in 32 steps. Each step is equivalent to 0,625% of voltage.

The circuit on the primary of the autotransformer is connected through the taps to the series winding of the regulator. The series winding is connected to the shunt winding which is directly connected to the regulated circuit, as shown in the *Fig. 1*. This is called regulator with standing excitation, knowing this, the excitation coil is located on the load side, it doesn't fell variations from the voltage source. The bobbin's polarities who determine the electric connection for the regulator works as voltage buck or boost. There is a switch that invert the polarity in the circuit, allowing the autotransformer works as voltage buck or boost. In *Fig. 1* there is a autotransformer in voltage boost mode, the switch that invert polarity is not shown (KERSTING, 2002).

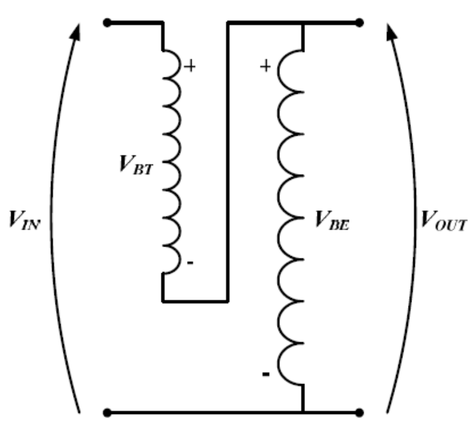

Figure 1 – Autotransformer

Three single-phase voltage regulators can be connected externally to form a three-phase bank configuration. Each regulator has its own compensator circuit, and the commutation occur independently in each phase. The choice of connection to be used must be done based on the nominal voltage of the circuit. For example, a SVR with potential transformer (PT) which transformer relation is 14400/120V must be connected in closed delta in a circuit with 13,8kV (line-line voltage), or in Wye-grounded in a circuit with 23,1kV (line-line voltage). The typical connections among single-phase regulators are following described.

Three single-phase voltage regulators can be connected in closed delta as shown in the *Figure 2*, where voltage regulators are set as voltage boost. The closed delta connection is typically used in feeders in delta configuration without neutral wire. Note that the voltage transformers for this connection are monitoring line to line voltage by side of the load. The current transformers don't monitor line to line current by side of the load.

The relations among voltages, currents and the side of source are necessary. The equations define the relation among voltage and currents for SVR. This relation can be satisfied depending on how the SVRs are connected. The Kirchhoff's law for line-line voltage is firstly applied in a closed loop, starting with a line-line voltage between A-Phase and B-Phase on the side of source, as shown in the *Figure 2*.

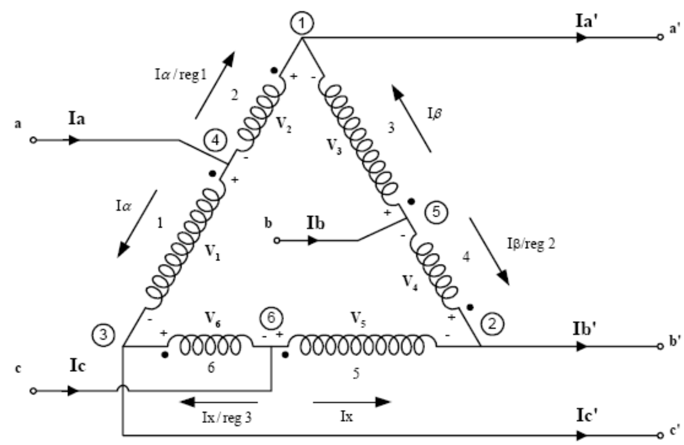

Figure 2 – VR circuit in closed delta

The follow relations are defined:

$$
\begin{aligned}
Tap_1 &= 1 + reg_1 \Rightarrow reg_1 = 1 - Tap_1 \\
Tap_2 &= 1 + reg_2 \Rightarrow reg_2 = 1 - Tap_2 \\
Tap_3 &= 1 + reg_3 \Rightarrow reg_3 = 1 - Tap_3
\end{aligned} \qquad (1)
$$

B. *Voltage Equation:*

- Voltage Output

$$V_3 = -\frac{V_{a'b'}}{Tap_2}$$
$$V_5 = -\frac{V_{b'c'}}{Tap_3} \quad (2)$$
$$V_1 = -\frac{V_{c'a'}}{Tap_1}$$

- In matrix form, the input voltage is:

$$\begin{bmatrix} V_{ab} \\ V_{bc} \\ V_{ca} \end{bmatrix} = \begin{bmatrix} -reg_1 & -1 & 0 \\ 0 & -reg_2 & -1 \\ -1 & 0 & -reg_3 \end{bmatrix} \cdot \begin{bmatrix} V_1 \\ V_3 \\ V_5 \end{bmatrix} \quad (3)$$

Substituting the equation 3 in the equation 2 results in the equations below, in its matrix form:

$$\begin{bmatrix} V_{a'b'} \\ V_{b'c'} \\ V_{c'a'} \end{bmatrix} = \begin{bmatrix} \frac{1}{Tap_2} & 0 & \frac{Tap_1 - 1}{Tap_1} \\ \frac{Tap_2 - 1}{Tap_2} & \frac{1}{Tap_3} & 0 \\ 0 & \frac{Tap_3 - 1}{Tap_3} & \frac{1}{Tap_1} \end{bmatrix}^{-1} \cdot \begin{bmatrix} V_{ab} \\ V_{bc} \\ V_{ca} \end{bmatrix} \quad (4)$$

We can conclude from equation 4 that there is a relation between voltage phases, in other words, the tap changing in a phase influences the voltage of another phase, which generates regulation of 15%.

C. Current Equations:

- Current Output:

$$I_{a'} = I_\beta + \frac{I_\alpha}{reg_1}$$
$$I_{b'} = I_\chi + \frac{I_\beta}{reg_2} \quad (5)$$
$$I_{c'} = I_\alpha + \frac{I_\chi}{reg_3}$$

- Current Input:

$$I_\alpha = \frac{I_a \cdot reg_1}{Tap_1}$$
$$I_{b'} = I_\chi + \frac{I_\beta}{Tap_2} \quad (6)$$
$$I_{c'} = I_\alpha + \frac{I_\chi}{Tap_3}$$

Substituting the equation 6 in equation 5, results in:

$$I_{a'} = \frac{I_b \cdot (Tap_2 - 1)}{Tap_2} + \frac{I_a}{Tap_1}$$
$$I_{b'} = \frac{I_c \cdot (Tap_3 - 1)}{Tap_3} + \frac{I_b}{Tap_2} \quad (7)$$
$$I_{c'} = \frac{I_a \cdot (Tap_1 - 1)}{Tap_1} + \frac{I_c}{Tap_3}$$

The current in matrix form:

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} \frac{1}{Tap_1} & \frac{Tap_2 - 1}{Tap_2} & 0 \\ 0 & \frac{1}{Tap_3} & \frac{Tap_3 - 1}{Tap_3} \\ \frac{Tap_1 - 1}{Tap_1} & 0 & \frac{1}{Tap_3} \end{bmatrix}^{-1} \cdot \begin{bmatrix} I_{a'} \\ I_{b'} \\ I_{c'} \end{bmatrix} \quad (8)$$

We can conclude from the equation 8 that a change on the tap level of a voltage regulator affects directly the current in the other phase, so, exist current relations between phases.

For automatic selection tap: when the planner choose for automatic selection tap and define the voltage bus controlled, it's necessary to perform a previous calculation for the tap, before the application of voltage and current equations. For SVRs connected in Wye or in open delta, just divide the target voltage by primary voltage and adjust this factor to the best position tap. For SVRs connected in closed delta, this is not possible because of the mutual inductance between phases, in other words, the definition of a tap position is influenced by the phase voltage adjacent. The way to contour this problem was to implement an evolutionary algorithm (EA) just to define the tap position. Then, with the tap defined by EA, the current and voltage equations are applied for SVRs connected in closed delta.

D. Power Flow

The analysis of a distribution system through its three-phase power flow is essential for the study of the voltage profile and to analyze alternatives to correct it, like installing voltage regulators.

A Power Distribution System (PDS) is usually composed of a main trunk, lateral, sub laterals and distributed loads along the feeders. Laterals are derivations of the main trunk, which don't always have three-phase connections.

In this work, it was implemented the three-phase power flow shown in (KERSTING, 2002), which is an iterative process based on the ladder technique for use in PDS. It considers the non-linearity of the distribution systems, the presence of branching and coupling between phases. According to (KERSTING, 2002), the techniques of load flow usually applied to transmission systems are not applied to radial distribution systems due to the convergence limitation of these algorithms.

The analysis of load flow of a distribution feeder allows the determination of the following system quantities:

- Voltage magnitude and angles in all busses;
- Active and reactive power flow in each section;
- Losses in each line section;
- Total active and reactive power of the feeder;
- Total losses.

The algorithm is based on the Kirchhoff's Laws to calculate the voltages and currents in all busses and line sections. Considering the system shown in *Figure 2*, the equations defining the currents and voltages in the entry bus (bus *n*) and output bus (bus *m*) are:

The load flow algorithm based on the ladder technique is run in two scanning processes of the system: backforward sweep and forward sweep. The forward sweep process scans the system in load to source order, determining the currents in the line sections and the voltage at the substation. On the other hand, the backward sweep process scans the system in source to load order, determining the voltages in the busses through the currents in the line sections calculated on the forward sweep process.

E. Evolutionary Algorithm (EA)

- Proposed Method:

Due to characteristics of the power flow backward/forward, realized the possibility to use the EA strategy to calculate the tap level of an automatic SVR.

In each power flow iteration, during the step forward, it executes the EA to find the best set of tap levels of the SVR. As the calculation of tap levels is done in each iteration, when the power flow converge, the set of tap levels from SVR will be defined.

Due to radial structure of distribution system and the utilization of backward/forward method, during each iteration, it's possible to know the voltage of primary bus from the SVR before calculate the voltage of secondary bus of it. This way, the search for the tap level of SVR is given in function of the voltage in the primary of it and the target voltage in the secondary.

Just defined the set of tap levels of some SVR, the secondary voltage can be calculated in function of the primary voltage, through the equation 4 and equation 8. This equation is used by EA during the calculation of objective function.

F. EA Formulation:

The EA was formulated as follow:

- Chromosomes: Chromosomes in the proposed method are represented by an integer sequence and the ith gene represents the SVR's tap level. Each gene is represented by a number from -16 to 16 that represent the chosen tap level for the SVR.
- Initial population of chromosomes: In the proposed method, an initial population of chromosomes is generated randomly. One of the chromosomes don't have his genes generated randomly, instead of his genes (regulator's tap level) are obtained through the relation between the voltage in the primary bus and the target voltage.
- Reproduction and Crossover: the proposed method uses the roulette wheel selection, elitist replacement and one point crossover.
- Mutation: Mutation introduces variations into the chromosome with a given probability by transforming a part of the chromosomes. The proposed method applies a random variation's range at each gene separately and the number of genes modified at each chromosome is random as well.
- Fitness Function: The fitness of each chromosome is calculated through the objective function, that is the sum of squared of difference between voltage target and voltage calculated in the secondary of the transformer, as the equation below.

$$\sum \left(V_{target} - V\right)^2 \qquad (9)$$

- Stopping criteria: The EA will be executed until it calculates 6 generations without modifications in the tap levels or until 30 generations. Due to the fast converge of EA, it's possible to apply the first stopping CRITERIA without harming the final result of optimization process, for acceleration of load flow calculation.

III. Tests and Results

The IEEE 34 Bus Distribution System (*Figure 3*) was used to test the performance of the Automatic Tap Voltage Regulator. The reference voltage was assumed 1,05 p.u. and the load was tested for 1,0 p.u., 1,6 p.u. and 2,2 p.u. The tap set of each phase and for each regulator is shown in Table 1.

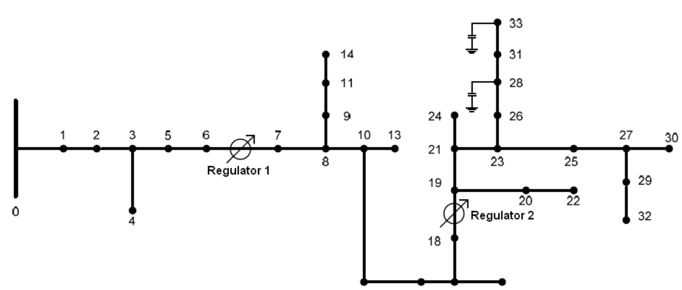

Figure 3 – IEEE 34 Bus Distribution Test System

Table 1 – Tap set for each load conditions

Load [pu]	Regulator	TAP DE Phase	TAP EF Phase	TAP FD Phase
1	1	16	16	16
	2	22	20	21
1,6	1	21	19	20
	2	26	25	24
2,2	1	27	24	24
	2	30	28	29

As result we have a comparison of voltage [pu] in a regulated and in a not regulated system, as shown in the *Figure 4*.

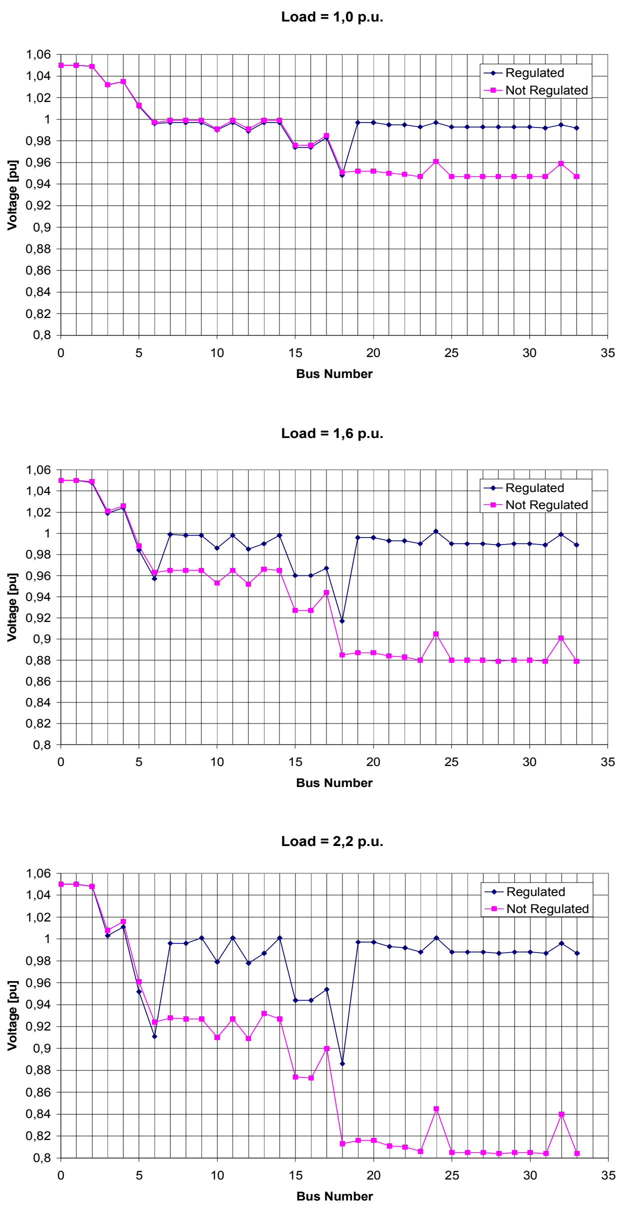

Figure 4 – Voltage bus for three load conditions

IV. Conclusion

In this paper, we have a comparison between an automated tap voltage regulator and the conventional fixed tap. Analyzing the *Figure 4*, it is easy to understand that the automated method is much more efficient under load changing conditions, keeping a good voltage profile of the network.

The voltage regulator connected in closed-delta requires more computational effort due to the calculation of the power flow in a closed-delta, which needs more iterations. Also, when a tap is changed, the line-line voltage from the others also changed which mean that more iterations are needed.

References

[1] ANEEL – Brazilian Electricity Regulatory Agency. It establishes the updated and consolidated the provisions according to the voltage levels of electricity on stand still state. Resolution nº505, November 26th, 2001.

[2] The software InterPlan is a computational system for studies of planning of short and medium term, which allows graphical viewing and editing of the network and also allows you to define the optimized network configurations to meet previously set goals. This software was developed by Daimon Engineering. Site: www.daimon.com.br

[3] C. S. Cheng and D. Shirmohammadi, "A Three Phase Power Flow Method for Real Time Distribution System Analysis," IEEE Transactions on Power Systems, vol. 10, no. 2 pp. 671-679, May 1995.

[4] D. Rajicic, R. Ackovski, and R. Taleski, "Voltage correction power flow", IEEE Transactions on Power Delivery, vol. 9, no. 2, pp. 1056-1062, April. 1994.

[5] M. A. Pereira, "Fluxo de potência em Sistemas de Distribuição de Energia Elétrica", Teses de Mestrado apresentada à UNICAMP em 1993.

[6] M. E. Baran and E. A. Staton, "Distribution transformer models for branch current based feeders analysis", IEEE transaction on Power Systems, vol. 12, no. 2, pp. 698-703, May. 1997.